NON-SCALING FFAG MAGNET CHALLENGES

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Abstract

The BASROC consortium in UK has embarked on the development of non-scaling FFAG accelerators as prototypes for hadron therapy and other applications. Two projects are underway: the construction of a 20 MeV electron machine, EMMA, and the design of a proton/heavy ion accelerator-PAMELA. EMMA will be assembled from room-temperature very short quadrupoles, whilst PAMELA requires unconventional, superconducting, combined function magnets. The injection and extraction magnets for EMMA need to fit into the 110mm straights in the lattice, with the injected and extracted beams being deflected through large angles.

INTRODUCTION

BASROC – the British Accelerator Science and Radiation Oncology Consortium [1] is a group of academic, medical and industrial specialists. Their current aim is to work towards the construction of a complete hadron therapy facility. The fixed field alternating gradient accelerator (FFAG) appears to be attractive for this purpose, as it combines some of the particular advantages of the cyclotron and synchrotron. However, transverse beam movement during acceleration is large in the scaling version, implying large magnets.

BASROC has therefore focused on the use of a 'non-scaling' alternative (nsFFAG), which has much reduced apertures; UK funding has now been obtained to support:

- The construction of a small prototype nsFFAG – EMMA [2], [3], [4]. This 'Electron Model for Many Applications' will be a 20MeV accelerator, used to learn how to design nsFFAGs for a variety of purposes, including hadron therapy. It is being built at STFC's Daresbury Laboratory, U.K. and will use the recently commissioned ALICE facility [5] to provide the electron beam for injection.
- The feasibility design of PAMELA - a 'Particle Accelerator for Medical Applications'. This accelerator is intended to be a prototype to demonstrate that an nsFFAG can be used for hadron therapy. The first stage of this work is the design of a 250 MeV proton accelerator, including detailed lattice and tracking studies, the design of the magnets and of a suitable r.f. system [6].

THE EMMA RING MAGNETS

The EMMA lattice is of a novel nature [7], made up of 84 combined function magnets, incorporating dipole and quadrupole field components in two F and D type families. The machine is planned to accelerate electrons between 10 and 20 MeV. To allow the experimental investigation of orbits and emittances, it was envisaged that injection and extraction could be performed at any energy between the operating limits.

The EMMA Combined Function Magnets.

In an FFAG, an orbit can be defined at a given particle momentum, but during acceleration the circulating beam moves radially in the quadrupoles, experiencing a variable dipole bending field at different radii. Due to the experimental nature of EMMA, wide independent variation of the dipole and quadrupole components in the magnets are required. An early task was to determine the geometry of poles and coils that would best provide this separate control. This can be achieved by designing dipoles with a built-in pole-face gradient and then introducing pole-face windings to provide independent change to the quadrupole component. However, it was clear that this was not a satisfactory solution for the EMMA magnets, as demonstrated by the parameters shown in Table 1.

Table 1: EMMA Magnet Strengths for the 10 MeV Orbit

Parameter	F magnet	D magnet	
Bend angle	-0.04994	0.1995	radians
B lengths	55.0	65.0	mm
Dipole flux density	0.0302	0.102	T
Max. quad gradient	9.3	5.8	T/m

This demonstrates that, with the anticipated apertures, the magnets have much stronger quadrupole field than dipole. It was therefore decided to build the magnets as off-centre quadrupoles, with apertures that would accept the full range of beam movement during acceleration. The quadrupole component would naturally be controlled by the current in the quadrupole coils, whilst the dipole component would be adjusted by having precision radial movement of each quadrupole. This allows the other magnet parameters to be determined, giving the values shown in Table 2.

Table 2: Design Parameters for the EMMA Ring Magnets

Parameter	F quad.	D quad.	
Inscribed radius	37	53	mm
Yoke length	55.0	65.0	mm
Offset of 15 MeV beam from magnetic centre	7.51	34.05	mm
Horizontal movement from the 15 MeV orbit	-2.6 to +2.7	-5.3 to +14.5	mm
Good gradient region w. r. t. magnetic centre.	-32.0 to +15.8	-56.0 to -9.9	mm

It can be seen from table 2 that the beam moves across the F quadrupole magnetic centre during acceleration, so a full quadrupole is required. However, in the D, the beam only occupies one half of the quadrupole, never crossing the magnetic centre; a half-quad, with a vertical magnetic mirror, could be used, promising significant cost savings. However, modelling showed that end effects were substantial; unless the mirror is very long, major field distortion occurs, and this could not be corrected. Hence, a full quadrupole is needed, even though only one half of its aperture will be used. The resulting layout of the 84 quadrupoles in the EMMA 6 m diameter lattice is shown in Fig 1.

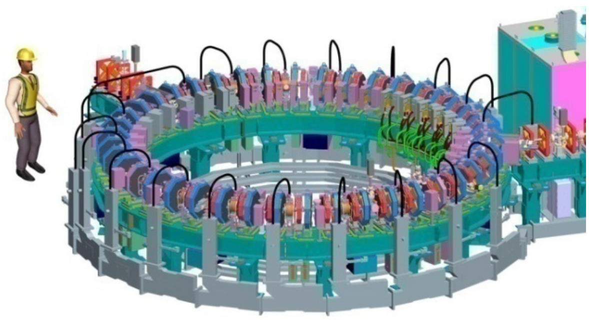

Figure 1: The EMMA lattice containing 42 F and 42 D magnets.

The Need for Clamp-plates

Clamp-plates (mirror-plates) are used generally at magnet ends to control the extent and configuration of stray fields. In EMMA, with the short straights between the magnets, the end field would penetrate into the straight section components: r.f. cavities; the injection and extraction kicker and septum magnets. This would result in distortion to the integrated quadrupole fields and seriously interfere with the straight section equipment, particularly the yokes of the fast magnets. It was decided to place a clamp plates around the outside of each magnet doublet. Figure 2 shows the plan view of a doublet, an r.f cavity and the next D magnet, demonstrating the position of the clamp-plates and the small space available for other components.

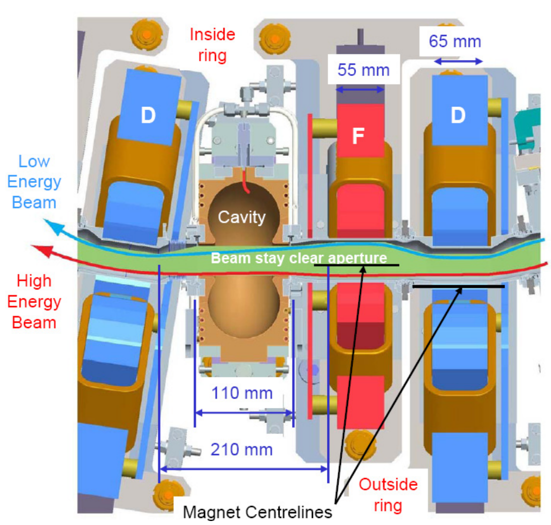

Figure 2: Plan view of an EMMA quadrupole doublet located to the right of an r.f. cavity, showing positions of clamp-plates and trajectories of the circulating beams.

The Design of the EMMA Prototype Magnets

The lengths of the magnet yokes are only ~ 25% greater than their inscribed radii; hence they are dominated by end effects. This was studied using a 3D modelling code [8]. This showed that the full amplitude quadrupole field was not achieved at the azimuthal centre of the magnets; the end effects penetrate throughout the length. The magnet designs therefore needed to generate a pole geometry that gives satisfactory integrated gradient over the required regions and predict the excitation necessary to generate the required integrated gradient strengths.

Standard quadrupole designs use a hyperbolic pole, terminated with a short tangent at the pole ends; this provides a single adjustment – the coordinate at the commencement of the tangent. During the design it became clear that this simple approach did not provide sufficient control of the integrated gradient quality [9].

An alternative strategy was developed: the hyperbolic pole face was replaced with a series of straight lines and the positions of vertices optimised. After further modelling, the arrangement adopted for both F and Ds used 5 points at symmetric positions on the pole face. The optimum shapes for the clamp plates were investigated and it was found that a full replication of the pole geometry gave best results. Subsequently, two prototypes were built, shown in Fig 3.

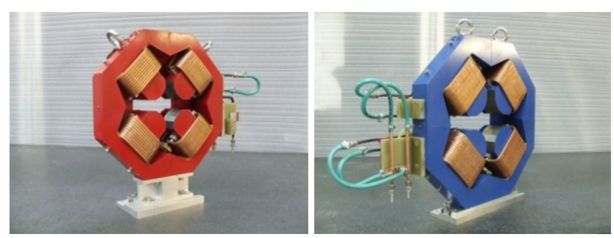

Figure 3: The EMMA prototype magnets (F left, D right).

Measurements were performed using a rotating coil system, on each magnet and with them paired on the measurement bench. For both magnets, the measured gradient dropped off quicker than the 3D models predicted. For the F magnet, there was a gradient variation of + 0.4% / -2% within the specified aperture of 32mm; this was judged to be acceptable.

The D magnet required improvement. At the outer radius of the coil (35mm), the gradient was shown to be reduced by 1% of its central value, indicating a much greater reduction at the edge of the required aperture of 56mm. Further development, with added pole shims followed by further measurement, was carried out. Subsequently, an acceptable gradient distribution was obtained, as reported elsewhere [10].

The EMMA Production Magnets

Most of the F magnets have now been assembled, and 34 have been delivered. The qualities of these magnets - the variations of integrated gradients, normalised to the integrated gradients at the magnet centres $\Delta\int g(x)/\int g(0)$, for the 34 F magnets, are shown in Fig 4.

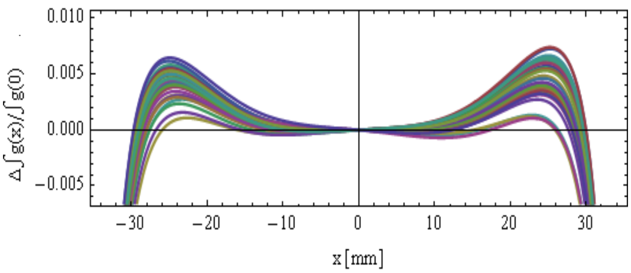

Figure 4: The gradient quality of 34 production Fs, expressed as Δ∫g(x)/∫g(0).

Assembly of the D magnets is now in progress, and measurements are presenting difficulties. The rotating coil has a radius of 35mm and hence, to cover the gradient aperture of 56mm, the coil has to be horizontally positioned at two centres; 0 and -20mm, and the resulting curves combined, as shown in Fig 5, with the separate curves overlaid, for two different Ds.

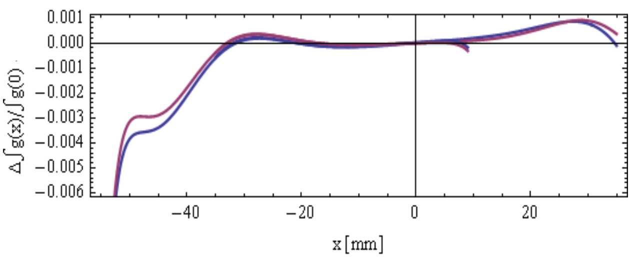

Figure 5: The gradient quality for 2 production Ds, expressed as Δ∫g(x)/∫g(0).

Gradient Strengths of the Production Magnets

Lattice investigations have indicated that variation in strengths between the ring magnets is likely to cause beam disturbance. So during measurement, the azimuthal positions of clamp plates are being adjusted to provide a strength uniformity of $1{:}10^4$. This is being achieved by the magnet manufacturer.

THE EMMA INJECTION AND EXTRACTION MAGNETS

Injection and Extraction Geometry

The EMMA injection and extractions systems follow the conventional approach of using a septum magnet to deflect the incoming or outgoing beam from the internal orbit and a pair of fast kicker magnets to deflect the orbit into the septum aperture. However, a suitable beam geometry is far from clear. With a maximum of 110mm available between ring magnets, there is a major difficulty in finding an acceptable injection path.

The possibility of the beam-line passing through a number of magnets was considered. However, this would result in the beam passing through fringe fields; these will be subject to wide amplitude variations during experimental work, so the beam-line geometry would alter whenever the lattice was adjusted. Furthermore, the radial positions of the ring magnets will be adjusted, to change the ratio of dipole to quadrupole field; so a variable geometry beam-line would be necessary. This is clearly impractical. The decision was therefore made to inject the beam in a single straight; likewise the extraction. This results in a very large deflection angle.

Injection and Extraction Magnet Details

The resulting septum parameters are given in Table 3. These are based on an eddy-current (passive) septum, excited by a two turn back-leg winding.

Table 3: EMMA Septum Magnet Parameters

Maximum beam deflection angle	77	degrees
Maximum flux density in gap	0.91	T
C core magnet gap height	22.0	mm
Internal horizontal beam ‘stay-clear’	62.5	mm
Turns on excitation coil	2	
Excitation half-sine-wave duration	25	µs
Excitation peak current	9.1	kA
Excitation peak voltage	900	V
Septum magnet repetition rate	20	Hz

Additionally, so as to accommodate the wide variation in injection and extraction geometries, the septum magnets will be adjustable in both radial position and angle of yaw in their vacuum enclosure.

Beam studies predicted the kicker strengths needed for the various lattices [11]. Large amplitude variations will be required and, in some circumstances, polarity reversals are necessary. The power supply specifications are very demanding, including the need to switch the kickers in one turn – of the order of 50 ns. The resulting kicker magnet specifications are given in Table 4.

Table 4: EMMA Kicker Magnet Parameters

Maximum beam deflection	105	mR
Maximum flux density in gap	0.054	T
Horizontal good field region	± 23	mm
Minimum vertical gap at the beam	25	mm
Length of ferrite yoke	100.0	mm
Horizontal deflection quality	± 1	%
Minimum flat-top (+0, -1%)	≥5	ns
Field rise/fall time (100% to 1%)	50	ns
Peak current (1 turn conductor)	1.1	kA
Peak voltage (with feed through)	23	kV
Kicker magnet repetition rate	20	Hz

Four kicker magnets and power supplies plus two septum magnets were to be purchased commercially (the septum supplies would be modifications of existing units). However, this was not possible and the design and build of the magnets has been carried out in house, but with the kicker power supplies still obtained externally. The in-vacuum septum design is now complete. A CAD model of this is shown in Fig 6.

The yoke will be assembled from 0.1mm silicon steel laminations, encased in a copper eddy-current shield box with a two turns back-leg coil. The magnet is mounted on a slide, allowing translation and rotation about a vertical axis, with compatible vacuum power feed-throughs.

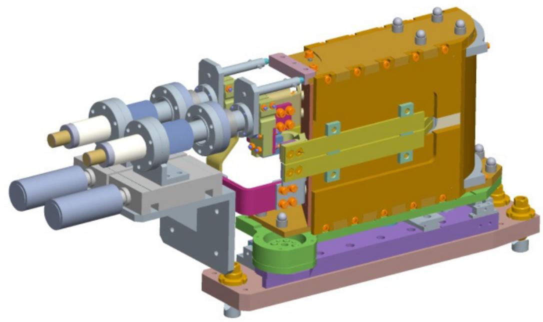

Figure 6: CAD model of the EMMA septum magnet outside its vacuum chamber.

A prototype kicker magnet is now constructed, see Fig 7. The magnet is suspended from a top-plate and is assembled from high frequency ferrite with eddy-current copper shielding and a single turn back-leg coil. It is designed to hold-off up to 25 kV in air, so that magnetic measurements can be carried out in the laboratory.

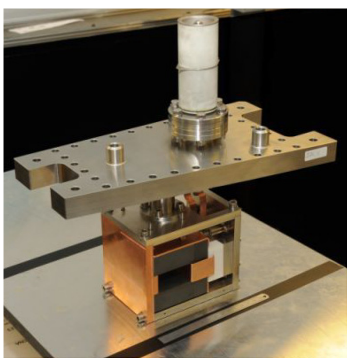

Figure 7: Photograph of the kicker magnet prototype with top-plate and coaxial feed-through; note the 15 cm ruler.

THE PAMELA RING MAGNETS

The project has now focused on accelerating protons to 250 MeV and carbon ions to 68MeV per nucleon, with up-grade potential to 400MeV/nucleon [12].

The PAMELA Lattice

Possible lattice layouts and magnet requirements for PAMELA have been studied [13],[14] and a 12 cell lattice has now evolved [15],[16]. The parameters of this lattice and magnets are shown in Table 5 [17].

Table 5: Current PAMELA lattice parameters

Lattice:	12 cells of triplets;
Magnet lengths:	314 mm;
Straights between magnets:	314 mm;
Straights between triplets:	1.7 m;
Radial offset F to D	66 mm;
Bore aperture diameter:	280 mm;
Combined functions:	4 components: dipole to octupole.
Peak field	4.25 T

The layout of a PAMELA triplet, including beam trajectories, is shown schematically in Fig 8.

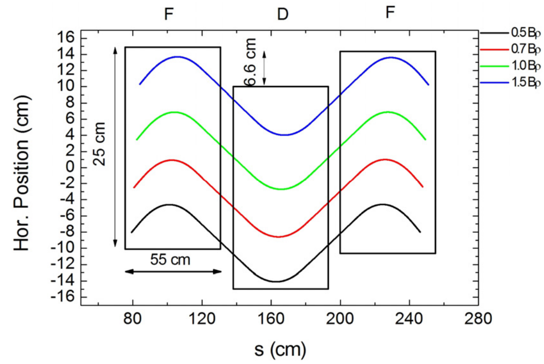

Figure 8: Current layout of PAMELA lattice triplet, showing beam trajectories.

Magnet Engineering

Each magnet is required to generate four field component, which must have independent amplitude control. Table 5 indicates that a field in excess of 4 T is required so, clearly, the magnets must be superconducting; the superposition of four independent harmonics therefore presents a challenge. The PAMELA team have addressed this problem by adopting a novel helical coil arrangement [18] [19]. Each harmonic is generated by one or more pairs of helical coils, counter wound, so that the axial components cancel but generating the required transverse component. The current paths can be described in Cartesian coordinates by the following equations:

$$x = R\cos\theta$$
$$y = R\sin\theta$$
$$z = \frac{h\theta}{2\pi} + \frac{R}{\tan\alpha}\sin(n\theta)$$

where R is the coil radius, θ is the azimuthal angle, h is the winding pitch and α is the tilt angle of the solenoid. The multipole order is given by the parameter ‘n’ (for a dipole n equals one, for a quadrupole two and so on) [20]. The cited references show that this geometry eliminates all unwanted harmonics in the end fields. The application of this to PAMELA, to generate the required field components, is shown in Fig 9. The parameters for this design are shown in Table 6.

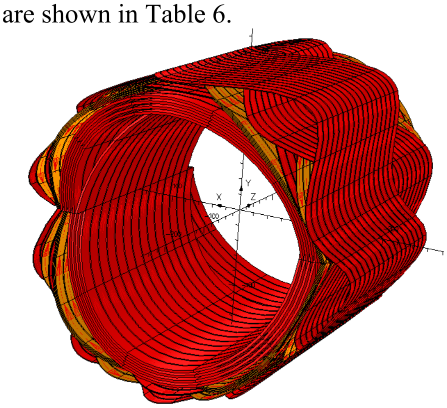

Figure 9: The arrangement of multiple counter-wound helical super-conducting coils to generate the required four field components in the PAMELA combined function magnets.

Table 6: Parameters of the multiple helical coil pairs for the PAMELA magnets shown in Fig 9

	2 pole	4pole	6pole	8pole
Length (mm)	560	565	555	564
No. of coil pairs	5	4	4	1
Inner radius (mm)	140	162	177	185
Outer rad. (mm)	160	173	183	187
Tilt (degrees)	50	50	60	60
Peak field at the wire (T)	5.1	5.4	5.0	4.2

CONCLUSIONS

This paper has detailed the challenges encountered in the design of two nsFFAGs. The work demonstrates that, as intended, nsFFAG magnets can be smaller and more compact than for a scaling machine. However, for hadron acceleration with an appreciable momentum gain, high field strengths are required. Further problems can be encountered if the lattice has very small magnet separations. This can, in some circumstances, create further difficulties in the design of other components.

The material presented indicates some of the solution adopted during the design of EMMA and PAMELA:

- EMMA and PAMELA require magnets to generate a number of harmonic fields, with independent amplitude control; EMMA uses pure quadrupoles with adjustable magnet positions, whilst PAMELA has multiple windings in the coils;
- EMMA has very short magnets, creating problems with end-field effects; PAMELA overcomes such problems by using a novel helical s.c. coil design;
- With the very small space in the EMMA lattice, clamp-plates are required to prevent interaction between the ring magnets and other components.
- Injection and extraction were found to be very difficult in EMMA and required large injection/extraction angles. This may not be a practical solution at higher energies, in which case it would be judicious to consider this problems carefully during lattice design.

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